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Evaluation of Currency and Stamp Papers

E. L. Graminski and E. E. Toth

Paper Evaluation Section
Institute for Materials Research

September 6, 1974

Progress report covering the period
January 1 – June 30, 1974

Prepared for

Bureau of Engraving and Printing
U. S. Department of the Treasury
Washington, D. C. 20401

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U. S. DEPARTMENT OF COMMERCE, Frederick B. Dent, Secretary
NATIONAL BUREAU OF STANDARDS, Richard W. Roberts, Director

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1. SUMMARY

Evaluation of Experimental Papers

As part of a continuing study for the Bureau of Engraving and Printing of the U.S. Department of the Treasury, two wood pulp papers (Paper A and Paper SDP) were evaluated for possible use in printing currency.

As technology progresses, the possibility exists that wood pulp papers may be as, or nearly as, durable as the present-day currency paper. A substantial savings in cost might result without compromising the circulation life of currency. As new papers which appear to have the characteristics essential to currency paper are developed, evaluations will be made to determine whether they are suitable for currency.

In the absence of a good means for evaluating experimental currency in circulation, laboratory methods must be relied upon. The flexing test, developed at the National Bureau of Standards, appears satisfactory for this purpose. It appears to rank papers in order of their probable durability. Those currencies exhibiting significant improvements in retention of properties over present-day currency in the flexing test would be expected to have a longer circulation life. However, no precise estimate could be given for the extent of increase in circulation life.

The performance of experimental currency printed on Paper A was comparable to present-day currency when flexed in the cross direction (CD) of the paper, but its performance was decidedly poorer when flexed in the machine direction (MD). A significant decrease in the MD folding endurance, as a result of MD flexing, suggests potential tensile failure and hole formation in currency during circulation. Thus, currency might be removed from circulation even though it had an acceptable level of stiffness, resulting in a corresponding decrease in circulation life. Further investigations must be conducted before a firm recommendation can be made on the use of Paper A for currency.

Paper SDP is an experimental paper and was not printed as large sheets were not available. Paper SDP was evaluated in order to assess the feasibility of producing the experimental paper on a larger scale for a full evaluation as currency paper.

The retention of properties with flexing of Paper SDP was not extraordinary, but it was recognized that this paper might be substantially improved by saturation with acrylic latexes. Preliminary results indicate that this is correct. Additional paper has been obtained from the manufacturer and further modifications and evaluations will be made during the next reporting period.

Resin Treatments of Handsheets

An investigation was conducted to determine the feasibility of improving stiffness retention by modifying paper with a combination of acrylic resin and a wet strength resin. When paper is modified with acrylic resins by beater addition, a very porous sheet frequently results. Apparently, the fibrils and debris formed during beating redeposits on the fibers. This results in a marked decrease in the formation of the film-like portion of paper which is so essential to the retention of paper stiffness when flexed. Formation of the film-like component must be induced if the ultimate benefit is to be achieved from the modification of paper with acrylic resins by beater addition. As the porosity of paper declines when treated with melamine wet strength resin, post-treatment of pulp, modified with an acrylic resin by beater addition, may give rise to a less porous sheet. This double treatment could result in a paper with superior stiffness retention with flexing.

The validity of the above hypothesis was assessed by using an acrylic resin in beater addition which produces a very porous handsheet. The results indicate clearly that post-treatment with the wet strength resin induces formation of the film-like material resulting in a less porous sheet. The double treatment resulted in a significant improvement in retention of stiffness with flexing. It is anticipated that other acrylic resins could give origin to an even greater improvement in stiffness retention as well as retention of all other properties. Additional investigations, using other acrylic resins, will be performed during the next reporting period.

2. EVALUATION OF CANDIDATE PAPERS FOR PRINTING CURRENCY

2.1 Background

Papers may be submitted to the Bureau of Engraving and Printing (BEP) or to the National Bureau of Standards (NBS) to be evaluated for use in currency. Only all rag papers were considered previously, but papers containing all or part wood pulp now are being accepted for evaluation.

A potential currency paper must (1) exhibit good printability, (2) show high retention of bending stiffness, and (3) maintain strength and internal tear during its circulation life.

The ideal procedure for evaluating a new paper for currency is to determine the circulation life of the currency during circulation. In order to do this, the currency must be coded in some way, and this creates a numismatic rarity. Therefore, the coded currency is removed from circulation in large quantities making an evaluation of its circulation life virtually impossible. Means are available to evaluate currency in circulation without creating a numismatic rarity, but special recognition equipment at each Federal Reserve Bank would be necessary.

In the absence of methods for successfully evaluating the performance of currency while in circulation, laboratory evaluations of paper durability must be relied upon. The flexing test developed at NBS [1] appears to evaluate satisfactorily the relative durability of paper. Since the circulation life of One Dollar Federal Reserve Notes printed on the present currency paper is approximately 18 months, a paper performing significantly better than the present currency paper in the flex test should have a longer circulation life, but the magnitude of the increase could not be estimated precisely.

Early evaluations of durability with the flexer were lengthy because of the large number of flexes and samples used in the evaluation. Experience has shown that an estimate of the retention of bending stiffness with flexing can be made after only 1,000 flexes. Furthermore, 10,000 flexes appear to be sufficient to indicate the tenacity of the paper. The total evaluation time is reduced to a practical level by using only these two levels of flexing in both the cross (CD) and machine (MD) directions of the paper.

A second change was also made in the flexing procedure. Paper is anisotropic with the result the MD modulus is approximately 2.5 times greater than the CD modulus. In an effort to flex paper at equivalent levels of internal stress, paper was formerly flexed over 3.18 mm rollers in the CD and over 7.94 mm rollers in the MD--a ratio of 1 to 2.5. Since currency is probably strained in both directions to the same degree, it was decided to evaluate the durability of currency paper using a 3.18 mm roller in both the MD and CD directions.

During this reporting period, two wood pulp papers were evaluated for possible use in currency. The first paper, designated Paper A, was submitted to BEP for evaluation. The paper was printed on the currency presses and the durability evaluation was performed on the printed paper.

The second paper (Paper SDP) also was an all wood pulp paper and was submitted to NBS for evaluation. Paper SDP is made from 100 percent long wood pulp fiber and is treated with an epoxy resin according to a patented process.

An estimate of stiffness retention with flexing was done on Paper SDP with a limited number of samples submitted by the manufacturer. The stiffness retention was not outstanding, and it is believed that the high porosity of this paper was partly responsible for the low retention of stiffness. Previous work has shown that saturation of paper with certain acrylic resins results in a decrease in paper porosity and an increase in stiffness retention with flexing [7, 8, 9]. It was therefore decided to determine the effect of saturating Paper SDP with acrylic resins on the retention of stiffness. Acrylic resins AC-61 and HA-16 were chosen for this study because good results were obtained with these resins in previous latex saturation experiments [9].

2.2 Experimental

The flexing samples (15.2 x 30.5 cm) were cut from either 32 subject sheets of printed currency or from 28 x 43 cm sheets of Paper SDP. The samples were randomized into sets of 10 when sufficient paper was available. Only three printed sheets of Paper A were available so that each set consisted of only four samples.

Flexing was performed on the NBS paper flexer over 3.18 mm diameter rollers in both the MD and CD for 1,000 and 10,000 double flexes. That portion of the specimen passing over both rollers was used for subsequent testing. The air permeability of each sample was measured in six different locations with a commercial air permeability tester. The sample was then cut into eight specimens as shown in Figure 1.

Cantilever stiffness was measured with the Carson-Worthington stiffness tester [12]. These specimens were then used for the determination of internal tear according to TAPPI T414 ts-65. A single specimen was used for each determination on an Elmendorf tear tester with a capacity of 200 g. Folding endurance was determined according to TAPPI T511 su-69 using an MIT folding endurance tester.

Load elongation was performed on a constant rate of loading apparatus according to TAPPI T404 ts-66, using a specimen 1.5 cm wide and a span length of 10 cm. Sonic modulus was determined on the edge tear specimens with a commercial apparatus according to ASTM Method F89-68 using the two-point procedure.

Saturation of Paper SDP with acrylic resins AC-61 and HA-16 was done with the aid of a laboratory size press using 10 percent emulsions. The paper was first weighed on an automatic pan balance, passed through the size press at an approximate rate of 30 cm per minute and a pressure of 6.5 kg/6.45 cm^2. The saturation sheet was dried on a drum drier at 95°C for approximately four minutes. The dried sheet was equilibrated 15 minutes at ambient conditions before weighing again on the pan balance to determine weight gain.

2.3 Results and Discussion

2.3.1 Present-Day Currency

The only significant change occurring in any CD property as a result of CD flexing of the present-day currency was a decline in CD cantilever stiffness. All other properties exhibited no significant change regardless of the number of flexes.

When flexed in the MD, a significant decrease in the initial modulus as well as in cantilever stiffness occurred after 1,000 double flexes. After 10,000 double flexes, the decline in modulus and cantilever stiffness increased further and a significant change occurred in practically every MD tensile property. These changes in MD tensile properties after 10,000 flexes clearly indicate that this paper is more durable in the CD than in the MD.

A cantilever stiffness of 0.9 g-cm for currency paper flexed 1,000 times in the CD compares extremely well with the average stiffness of redeemed currency [2, 3]. But, while good agreement in cantilever stiffness is found between CD flexed and redeemed currency, there is no agreement between any other property of laboratory flexed and redeemed currency, at least at the levels of flexing investigated. At very high levels of flexing there is rather good agreement between flexed and redeemed currency [2].

One of the causes for the disparity between flexed and redeemed currency at lower levels of flexing is the difference in the uniformity of currency flexing during circulation and on the NBS paper flexer. In addition to being bent or flexed, currency in circulation is crumpled and folded severely causing localized deterioration that has a significant effect on its tensile properties [4, 5]. Folded areas of redeemed currency are the weakest parts of the note as 90 percent of the tensile test strips from redeemed currency broke at one of the three principal folds found in the bills [2]. The folds, which run perpendicular to the length of a note, are found in the center and one in each half of the note.

The flexing test does not duplicate the wear currency receives in circulation, but rather it ranks papers in order of their durability. By comparing the laboratory durability of an experimental currency with that of present-day currency, an estimate of the performance of new currency can be made. All things being equal, currency printed on a paper having a substantially improved stiffness retention in laboratory flexing would be expected to have a longer circulation life than present-day currency.

Present-day currency paper has very good durability as indicated by a substantial circulation life of currency and by the difficulties experienced in attempting to destruct redeemed currency. Certainly, one approach to producing an improved currency paper is by modifying the present-day currency paper to bring about a significant improvement in stiffness retention.

2.3.2 Experimental Currency A

The retention of properties of currency printed on experimental currency paper A after being flexed in the CD was comparable to the retention of properties of flexed regular currency (Tables 3 and 4). Notable exceptions were retention of CD breaking strength and energy to break after 10,000 flexes (Figure 2).

Even though retention of cantilever stiffness for both currencies were comparable when flexed in the CD, a longer circulation life might be expected for the experimental currency. The initial cantilever stiffness of the experimental currency is substantially higher than regular currency, and its stiffness is greater than regular currency after each interval of flexing. This implies that the experimental currency should be in an acceptable condition at the point in time where regular currency is being redeemed for limpness. It is assumed that the integrity and appearance of the experimental notes would be at an acceptable level.

Retention of physical properties for the experimental currency in the MD following flexing in the MD was not comparable to regular currency (Figure 3). Significant decreases in initial modulus, breaking strength, and energy to break occurred after only 1,000 flexes. Furthermore, a significant decrease in MD folding endurance occurred after 10,000 flexes which could be of paramount importance. Two-dimensional folding of a note, in the length and width directions, gives rise to the formation of a hole in regular currency at the point where the two folds intersect [6]. Because of the marked decrease in MD folding endurance with MD flexing, the incidence of hole formation in the experimental currency might occur at a rate high enough to cause its circulation life to be substantially lower than regular currency despite an acceptable level of stiffness retention. Furthermore, a greater incidence of tensile failure may occur with the experimental currency as a result of flexing and folding during circulation. These points must be examined thoroughly before any consideration can be given to using Paper A for currency.

Future evaluations of printed experimental currency paper should be made on no less than 10, and preferably 20, sheets of 32 subject currency. Too few samples may lead to erroneous conclusions on the significance of differences in properties. Furthermore, a method of sampling for obtaining the 10 or 20 sheet samples should be developed.

As a result of the above evaluation, it does not appear that Paper A should be used for currency. The only advantage in using this paper may be a lower price. As the paper accounts only for approximately 15 percent of the total cost of new currency to the Federal Reserve Banks, the cost benefit realized in using a less expensive currency paper may be liquidated by the increased costs incurred in redemption and verification. A cost benefit analysis for the overall system is necessary in order to determine the feasibility of changing variables such as paper in printing currency.

2.3.3 Paper SDP

Additional paper was received from the manufacturer for the saturation investigation, but it was not identical to the first paper used in the preliminary evaluation. The porosity of the second paper was considerably lower than the first and this was not detected until the saturations and flexing were completed. The lower porosity of the paper made it difficult to obtain the desired weight gain of acrylic resin with saturation. The target was a 10 percent weight gain but only a 6.4 percent weight gain was attained with HA-16 and 8.7 percent with AC-61. Furthermore, saturation was very irregular due to a very uneven wetting of the paper.

Although the desired level of latex saturation was not achieved, it was decided to proceed with the evaluation since an estimate of the effect of saturation on stiffness retention was possible. The results are found in Tables 5 and 6 and the standard deviation of the results are given in Tables 7 and 8.

Saturation with either AC-61 or HA-16 resulted in improved stiffness retention with flexing. Although the weight gain of HA-16 was lower than with AC-61, the improvement in stiffness retention was greatest with Paper SDP saturated with HA-16. The results indicate Paper SDP may be suitable for currency providing it is modified with acrylic resins.

The above investigation will be repeated with additional paper which has the same porosity as the paper used in the preliminary evaluation.

3. MODIFICATION OF HANDSHEETS WITH ACRYLIC RESINS AND MELAMINE WET STRENGTH RESIN

3.1 Background

Scanning electron photomicrographs of currency paper indicate the presence of a film-like material or matrix in addition to the fibers [10]. The matrix is composed of fibrils and cell wall debris formed during the beating of pulp. The matrix spans the areas between the fibers causing a shortening of the effective fiber segment length and decreases the fibers ability to move laterally or to twist when strained. The shortening of the fiber segmental length leads to an increase in bending stiffness, as the apparent fiber stiffness increases with decreasing fiber length. The constraint of fiber twisting and lateral movement makes it more difficult to deform paper,and as a result, the modulus of paper will be greater than in a situation where the fibers are free to twist and move laterally.

When currency paper is flexed, cracks form in the matrix resulting in decreases in modulus and cantilever stiffness [10]. Similar cracking has been observed in redeemed currency [11]. The magnitude of the decline depends upon the extent of matrix deterioration. Increasing the cracking resistance of the matrix would result in an improved stiffness retention of paper with flexing. As the main cause for currency redemption is loss of stiffness, an improvement in the retention of stiffness of currency paper would result in an increased circulation life. An apparent means of achieving an improved stiffness retention is to improve the resistance to deterioration of the matrix in flexing.

Previous studies show that the melamine wet strength resin in dry-print currency paper probably accounts for the increased circulation life of currency printed on that paper [8]. The addition of melamine resin to currency beater stock also results in a substantial decrease in paper porosity. Apparently, melamine resin induces the fibrils and debris to form matrix to a greater degree. The increase in matrix formation, along with the interaction of the wet strength resin with the fibrous components of paper, probably account for the improvement in durability of dry-print currency paper.

One method for improving the tenacity of the matrix is by encapsulating the matrix components, prior to paper formation, with a suitable synthetic polymer. In effect, modification of paper with acrylic resins by beater addition involves just such an encapsulation of the fibers. However, beater addition with acrylic resins causes paper to become more porous. Scanning electron photomicrographs of handsheets modified with acrylic resins by beater addition indicate a marked decline in matrix formation [9]. Apparently, the matrix components redeposit on the fibers preventing matrix formation. Before an encapsulation process can produce the desired changes in the mechanical properties of the matrix, a means must be devised to induce matrix formation of the encapsulated matrix material.

Conceivably, enhancement of matrix formation could be accomplished by treating the encapsulated pulp suspension with melamine wet strength resin. Since this resin apparently induces matrix formation in conventional papermaking, it may also serve the same purpose with the latex treated pulp.

Latex E-631 was chosen for this investigation because prior studies showed very porous sheets resulted when used in beater addition experiments [7, 9]. Latex E-631 would probably never be considered in a modification of a currency type paper to achieve the properties sought. It was selected merely to test the feasibility of the above hypothesis.

3.2 Experimental

A bleached kraft wood pulp was beaten in a PFI laboratory mill at 10 percent consistency with no clearance between bedplate and roll for 10,000 revolutions at 3.4 kilograms force and a relative velocity of roll to bedplate of 6 m/sec. Forty grams of pulp were beaten for each of the variables investigated. Six aliquots were taken from each beater run sufficient to make a 12 x 12 inch handsheet of 70 g/m^2. An aliquot of beater stock was diluted with 600 cm^3 distilled water and disintegrated for 7,500 revolutions in a British disintegrator. The pH was adjusted to 9 using 1 $\underline{N}$ NaOH. A retention aid was added to the pulp slurry in the amount of 2 percent based on latex solids to be deposited on the fibers. The retention aid was added from a sufficient quantity of a 1 percent solution diluted with 30 cm^3 distilled water. Only two thirds of the retention aid was added at the start. The mixture of pulp suspension and retention aid was stirred 5 minutes prior to latex addition to exhaust the retention aid from solution. The pH of the mixture was then decreased to 4.0 with 0.5 $\underline{N}$ H_2SO_4.

The acrylic emulsion was diluted with approximately 50 cm^3 distilled water and added to the pulp suspension in three equal portions with moderate stirring. Five minutes was allowed between each addition to exhaust the acrylic latex. Only moderate stirring was used in order not to remove any adsorbed polymer by shearing. After all of the latex was added, the remainder of the retention aid was added and the mixture was stirred for an additional 5 minutes. Handsheets were then prepared if no further treatment was necessary.

Treatment with wet strength resin was as follows. To the aliquot, which contained beaten fiber only, or beaten fibers treated with acrylic latex, was added sufficient 12 percent solution of melamine resin to contain 3 percent resin based on the weight of the fiber. The pH of the mixture was 3.4 whether the stock contained acrylic resin or not and was stirred frequently during a 30 minute interval. At the end of that time, one drop of 0.5 $\underline{N}$ H_2SO_4 was added and stirred for about 1 minute.

The mixture was then transferred to the deckle box of the handsheet machine and a sheet was formed. The wire containing the formed sheet was placed on a blotter, covered with a felt, and consolidated by pressing the sheet with a 30 cm long roller weighing 22.5 kg. The sheet was removed from the wire, placed between felts, and passed through the roll press of the handsheet machine at the minimum pressure possible. The pressed sheet was dried on a drum drier at 95°C for approximately 4 minutes.

One half of each sheet was used to flex 1,000 times over 3.18 mm roller and constrained by a 700 g free hanging weight on the NBS paper flexer. The other half served as a control. The results are given in Tables 9 and 10 and the standard deviation of the results are given in Tables 11 and 12.

3.3 Results and Discussion

Handsheets modified with acrylic resin E-631 by beater addition followed by treatment with melamine wet strength resin results in a handsheet with a significantly lower air permeability than when treated with E-631 alone. In fact, the porosity of the acrylic-melamine resin handsheets is significantly lower than the handsheets treated with only melamine resin. Apparently, the lower porosity is due to enhanced matrix formation.

The double treatment resulted in an increase in cantilever stiffness, breaking strength, and energy to break. The effect of the double treatment on modulus is uncertain since there is a significant increase in the modulus of the specimens obtained in the width direction of flex samples but not in the length direction. A larger number of handsheets will be necessary to test for the significance in changes in modulus.

Acrylic resin E-631 is a very soft resin so that any increase in modulus, strength, and cantilever stiffness would be marginal. Nevertheless, it still produced significant improvements in retention of stiffness with flexing which indicates even better improvements are possible with other acrylic resins. This investigation will be continued during the next reporting period using other acrylic resins.

4. WORK IN PROGRESS

Considerable time was devoted to determining the effect of wet pressing on the structure and properties of handsheets during this reporting period. Previous work showed that wet pressing has a significant effect on the structure of paper [9]. Since the results of investigations on handsheets will be affected by their structure every effort must be made to determine the variables that can affect the structure in handsheet preparation. Sufficient information must be obtained to enable differentiation between effects produced by chemical modification and those produced by structural changes in handsheet preparation. This information is necessary in order to conduct meaningful mill trials to verify laboratory results.

Since the investigation on wet pressing has not been completed, reporting will be delayed until the next reporting period. The results will then be contained in a single report.

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Table 1. Tensile properties of flexed and unflexed present-day currency.

No. of Flexes	No. of Specimens		Extensional Stiffness		Initial Modulus		Breaking Strength		Elongation to Break		Energy to Break		Load at Yield		Elongation at Yield		Plastic Stiffness		Plastic Modulus	
			kg		$kg/cm^2 x10^{-3}$		kg		%		kg-cm		kg		%		kg		$kg/cm^2 x10^{-3}$	
	MD	CD	MD	CD	MD	CD	MD	CD	MD	CD	MD	CD	MD	CD	MD	CD	MD	CD	MD	CD
Flexed in CD over 3.18 mm rollers																				
0			885	435	47.8	23.4	11.5	6.6	3.4	7.7	2.6	3.7	6.7	4.3	0.8	1.0	183	35	9.9	1.9
s[1]	10	9	47	27	2.7	1.6	0.5	0.2	0.3	0.8	0.3	0.5	0.3	0.2	0.04	0.09	19	3	2.8	0.2
1,000			817	391	46.3	21.9	11.1	6.7	3.4	7.7	2.4	3.6	6.2	4.4	0.8	1.2	187	37	10.6	2.1
s	7	9	66	27	3.0	1.9	0.6	0.2	0.3	0.8	0.3	0.5	0.4	0.2	0.09	0.1	15	4	0.7	0.2
10,000			812	345	45.5	19.5	11.4	6.5	3.5	7.7	2.6	3.5	6.7	4.3	0.9	1.3	177	36	9.9	2.0
s	9	10	33	8	1.9	0.7	0.5	0.3	0.3	0.8	0.3	0.5	0.4	0.3	0.05	0.08	13.5	4.0	0.9	0.2
Flexed in MD over 3.18 mm rollers																				
0			890	448	49.2	24.9	11.4	6.8	3.5	7.8	2.6	3.8	6.6	4.5	0.8	1.1	179	34	9.9	1.9
s	8	10	34	16	1.8	0.9	0.5	0.2	0.3	0.5	0.3	0.3	0.5	0.3	0.06	0.07	14	5	0.8	0.3
1,000			715	445	41.8	25.8	11.3	6.6	3.6	8.3	2.6	3.9	6.5	4.1	0.9	0.9	178	35	10.4	2.0
s	9	9	44	23	3.3	1.9	0.6	0.2	0.3	1.0	0.3	0.5	0.5	0.2	0.03	0.05	11.4	4.5	0.7	0.3
10,000			639	421	36.3	23.6	9.1	6.4	2.5	7.9	1.4	3.6	5.6	4.1	0.9	1.0	216	34	12.1	1.9
s	9	10	43	22	2.7	1.7	0.6	0.4	0.3	0.7	0.3	0.4	0.4	0.3	0.09	0.08	19	5	1.1	0.3

[1] $s = \sqrt{\frac{n\Sigma x^2-(\Sigma x)^2}{n(n-1)}}$

Table 2. Physical properties of flexed and unflexed present-day currency.

No. of Flexes	Sonic[1] Modulus		Elmendorf Tear		Fold Endurance		Cantilever Stiffness		Air Permeability
s 1,000	$kg/cm^2 x 10^{-3}$		g		1000 grams double folds		g-cm		$cm^3/min(10cm^2)$
	MD	CD	MD	CD	MD	CD	MD	CD	
Flexed in CD over 3.18 mm rollers									
0	15.0	7.6	74	73	6330	6560	2.5	1.2	8
s[2]	0.2	0.4	7	11	1420	2200	0.3	0.06	2.1
1,000	13.7	7.1	73	74	5850	6620	2.2	0.9	7
s	0.7	0.4	11	10	1550	1920	0.2	0.07	0.7
10,000	13.6	6.8	72	71	6440	6720	2.1	0.8	9
s	0.6	0.3	7	14	1500	2100	0.1	0.04	2
Flexed in MD over 3.18 mm rollers									
0	13.9	7.9	76	74	5580	5550	2.4	1.2	8
s	0.8	0.2	12	8	900	1220	0.2	0.05	0.9
1,000	12.8	7.6	73	67	5940	6580	1.8	1.1	7
s	0.8	0.3	13	3	1090	2240	0.1	0.09	1.4
10,000	12.3	7.3	68	69	4750	6370	1.5	1.1	7
s	0.4	0.4	10	8	1180	1510	0.08	0.1	0.7

[1] Sonic modulus is based on cellulose density of 1.54.

[2] $s = \sqrt{\frac{n\Sigma x^2 - (\Sigma x)^2}{n(n-1)}}$ with n = 10.

Table 3. Tensile properties of flexed and unflexed currency printed on wood pulp paper A.

No. of Flexes	No. of Specimens		Extensional Stiffness		Initial Modulus		Breaking Strength		Elongation to Break		Energy to Break		Load at Yield		Elongation at Yield		Plastic Stiffness		Plastic Modulus	
			kg		$kg/cm^2 x10^{-3}$		kg		%		kg-cm		kg		%		kg		$kg/cm^2 x10^{-3}$	
	MD	CD	MD	CD	MD	CD	MD	CD	MD	CD	MD	CD	MD	CD	MD	CD	MD	CD	MD	CD
Flexed in CD over 3.18 mm rollers																				
0			1156	469	64.5	27.6	14.2	8.8	2.2	5.1	1.8	2.8	8.0	3.5	0.7	0.7	392	117	21.9	6.9
s[1]	3	3	99	25	3.5	1.9	0.9	0.7	0.3	1.0	0.4	0.7	0.7	0.2	0.03	0.05	36	19	1.3	0.7
1,000			1136	425	63.6	25.5	14.9	8.8	2.3	4.8	2.0	2.5	7.7	3.5	0.7	0.8	430	135	24	8
s	4	4	82	30	2.4	3.0	1.0	0.3	0.2	0.6	0.1	0.3	0.7	0.4	0.07	0.15	52	18	2.0	0.7
10,000			1057	384	61.7	23.9	13.6	7.5	2.2	4.7	1.7	2.1	7.1	3.1	0.7	0.8	442	110	25.8	6.9
s	5	5	61	23	2.5	2.0	0.9	0.6	0.3	0.5	0.4	0.4	0.2	0.1	0.04	0.06	28	5	1.3	0.5
Flexed in CD over 3.18 mm rollers																				
0			1230	503	71.3	27.4	15.9	8.3	2.5	4.8	2.3	2.4	7.4	3.5	0.6	0.7	416	117	24.1	6.4
s	4	4	135	40	4.1	1.0	1.4	0.4	0.1	1.1	0.1	0.6	0.4	0.4	0.06	0.03	60	18	2.3	0.7
1,000			855	455	50.2	25.4	13.8	8.1	2.4	5.1	1.9	2.6	7.8	3.2	0.9	0.7	388	107	22.8	6.0
s	4	4	76	14	5.2	1.1	1.1	0.7	0.2	0.5	0.3	0.4	0.6	0.1	0.2	0.05	28	9	2.1	0.5
10,000			741	445	42.9	25.2	9.1	8.3	1.6	5.2	0.8	2.6	5.5	3.1	0.8	0.7	464	109	26.8	6.2
s	7	5	110	43	6.3	2.9	0.6	0.5	0.1	0.6	0.1	0.5	0.5	0.1	0.1	0.06	65	9	3.5	0.4

[1] $s = \sqrt{\frac{n\Sigma x^2-(\Sigma x)^2}{n(n-1)}}$

Table 4. Physical properties of flexed and unflexed currency printed on wood pulp paper A.

No. of Flexes	No. of Specimens		Sonic[1] Modulus		Elmendorf Tear		Fold Endurance		Cantilever Stiffness		Air Permeability
1,000s			$kg/cm^2 x10^{-3}$		g		1000 grams double folds		g-cm		$cm^3/min(10cm^2)$
	MD	CD	MD	CD	MD	CD	MD	CD	MD	CD	
			Flexed in CD over 3.18 mm rollers								
0			18.9	8.7	52	60	4970	5280	3.4	1.4	14
s[2]	4	4	1.4	0.4	0.5	2.7	820	1370	0.6	0.2	2.5
1,000			18.1	7.8	57	65	4110	6020	3.3	1.1	15
s	4	4	0.7	0.4	7.2	8.2	460	1940	0.7	0.1	1.4
10,000			17.9	7.4	54	59	5090	4320	2.7	0.9	13
s	4	4	0.8	0.4	8.7	5.0	340	980	0.3	0.04	1.3
			Flexed in MD over 3.18 mm rollers								
0			18.3	7.5	56	63	4690	5610	3.7	1.4	13
s	4	4	1.0	0.4	6.0	4.1	370	1300	0.6	0.2	1.5
1,000			15.3	7.9	46	60	4290	5020	2.3	1.2	13
s	4	4	1.0	0.2	3.2	9.7	1360	740	0.3	0.1	1.0
10,000			12.7	8.0	62	48	2270	4770	1.8	1.3	15
s	4	4	0.5	0.5	6.2	5.6	480	810	0.2	0.2	2.8

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[1] Sonic modulus is based on cellulose density of 1.54.

[2] $s = \sqrt{\frac{n\Sigma x^2 - (\Sigma x)^2}{n(n-1)}}$

Table 5. Tensile properties of wood pulp paper SDP flexed 1,000 times in MD and CD over 3.18 mm rollers.

Direction of Flexing	Treatment	Extensional[1] Stiffness		Initial Modulus		Breaking Strength		Elongation to Break		Energy to Break		Yield Load		Elongation at Yield		Plastic[2] Stiffness		Plastic Modulus	
		kg		kg/cm^2x10^{-3}		kg		%		kg-cm		kg		%		kg		kg/cm^2x10^{-3}	
		MD	CD	MD	CD	MD	CD	MD	CD	MD	CD	MD	CD	MD	CD	MD	CD	MD	CD
unflexed	none	1050	584	91	51	8.8	6.0	1.6	4.2	0.9	1.7	6.0	3.3	0.7	0.6	275	74	24	6
unflexed	AC-61	970	592	75	46	8.6	6.7	1.9	4.3	1.1	1.9	5.2	3.5	0.5	0.6	245	86	19	7
unflexed	HA-16	933	575	72	44	9.1	6.9	2.1	4.6	1.2	2.1	5.4	3.4	0.6	0.6	243	84	19	7
CD	none	1005	423	85	36	7.9	6.0	1.4	4.5	0.7	1.7	5.3	3.0	0.5	0.7	300	78	25	7
CD	AC-61	954	508	77	39	8.7	6.5	2.0	4.2	1.1	1.8	5.1	3.2	0.5	0.6	242	91	19	7
CD	HA-16	940	473	72	36	8.7	6.5	2.0	4.4	1.1	1.8	5.2	3.1	0.5	0.7	245	89	19	7
MD	none	616	502	52	43	7.5	5.7	1.6	4.5	0.7	1.7	4.7	3.0	0.8	0.6	322	69	27	6
MD	AC-61	757	566	58	43	7.9	6.7	2.0	4.5	0.9	2.0	4.2	3.3	0.5	0.6	259	84	20	6
MD	HA-16	735	522	56	40	8.0	6.4	2.0	4.6	1.0	2.0	4.4	3.2	0.6	0.7	253	80	19	6

[1] Initial slope of load-strain curve.

[2] Slope of latter portion of load-strain curve.

Table 6. Physical properties of wood pulp paper SDP flexed 1,000 times in the MD and CD over 3.18 mm rollers.

Direction of Flexing	Treatment	Elmendorf Tear		Fold Endurance		Cantilever Stiffness		Air Permeability
		g		1000 grams double folds		g-cm		$cm^3/min(10cm^2)$
		MD	CD	MD	CD	MD	CD	
unflexed	none	51	48	880	1120	2.2	1.2	256
unflexed	AC-61	46	45	1230	1620	2.5	1.6	79
unflexed	HA-16	46	48	1230	1560	2.4	1.5	93
CD	none	50	47	910	1070	2.0	0.7	275
CD	AC-61	44	46	1460	1560	2.2	1.0	89
CD	HA-16	42	45	1470	1300	2.2	1.1	97
MD	none	48	44	840	1170	1.1	1.1	251
MD	AC-61	46	42	1060	1990	1.6	1.3	70
MD	HA-16	46	42	1280	1840	1.6	1.4	89

Table 7. Standard deviation[1] for tensile property data in Table 5 for flexed and unflexed wood pulp paper SDP.

Direction of Flexing	Treatment	No. of Specimens		Extensional Stiffness		Initial Modulus		Breaking Strength		Elongation to Break		Energy to Break		Yield Load		Elongation at Yield		Plastic Stiffness		Plastic Modulus	
				kg		$kg/cm^2 x10^{-3}$		kg		%		kg-cm		kg		%		kg		$kg/cm^2 x10^{-3}$	
		MD	CD	MD	CD	MD	CD	MD	CD	MD	CD	MD	CD	MD	CD	MD	CD	MD	CD	MD	CD
unflexed	none	9	10	38	19	4.3	1.8	0.6	0.5	0.2	0.6	0.2	0.4	0.5	0.06	0.06	0.02	30	4	2.8	0.4
unflexed	AC-61	8	9	60	26	4.4	2.3	0.8	0.5	0.3	0.5	0.2	0.3	0.4	0.09	0.04	0.04	23	4	1.8	0.3
unflexed	HA-16	10	10	85	23	6.4	1.5	0.8	0.3	0.2	0.3	0.2	0.2	0.4	0.1	0.1	0.08	15	4	1.2	0.3
CD	none	10	10	38	27	3.4	2.3	0.6	0.3	0.2	0.3	0.2	0.2	0.4	0.1	0.03	0.07	32	6	2.8	0.5
CD	AC-61	10	10	34	15	2.6	1.1	0.6	0.4	0.5	0.5	0.2	0.3	0.4	0.2	0.09	0.07	22	4	1.7	0.3
CD	HA-16	10	9	36	46	3.0	3.2	0.9	0.5	0.6	0.4	0.2	0.3	0.4	0.1	0.09	0.09	13	6	1.7	0.4
MD	none	9	9	64	35	5.7	3.2	0.3	0.3	0.7	0.4	0.3	0.4	0.4	0.06	0.1	0.08	30	3	2.5	0.4
MD	AC-61	10	9	32	27	3.3	1.9	0.5	0.5	0.2	0.6	0.1	0.4	0.2	0.1	0.09	0.05	20	5	1.5	0.4
MD	HA-16	9	7	55	38	4.5	3.2	0.3	0.7	0.1	0.7	0.09	0.4	0.4	0.1	0.07	0.1	25	6	1.9	0.4

---

[1] $S = \sqrt{\frac{n\Sigma(x)^2-(\Sigma x)^2}{n(n-1)}}$

Table 8. Standard deviation[1] for physical property data in Table 6 for flexed and unflexed wood pulp paper SDP.

Direction of Flexing	Treatment	No. of Specimens		Elmendorf Tear		Fold Endurance		Cantilever Stiffness		Air Permeability
				g		1000 grams double folds		g-cm		$cm^3/min(cm^2)$
		MD	CD	MD	CD	MD	CD	MD	CD	
unflexed	none	10	10	4.0	6.3	181	456	0.13	0.10	19
unflexed	AC-61	10	10	4.7	3.1	270	466	0.28	0.13	16
unflexed	HA-16	10	10	2.5	9.8	404	782	0.18	0.20	27
CD	none	10	10	11.7	5.0	911	285	0.16	0.07	11
CD	AC-61	10	10	8.9	4.7	494	339	0.21	0.09	19
CD	HA-16	10	10	2.8	5.5	385	704	0.15	0.13	24
MD	none	10	10	6.0	10.3	283	252	0.08	0.14	23
MD	AC-61	10	10	7.6	4.6	310	607[2]	0.18	0.13	21
MD	HA-16	10	10	5.7	5.8	390	531	0.12	0.12	25

[1] $s = \sqrt{\frac{n\Sigma x^2 - (\Sigma x)^2}{n(n-1)}}$

[2] Based on 8 specimens.

Table 9. The effect of treating wood pulp handsheets with acrylic resin E-631 and melamine wet strength resin on the retention of tensile properties with flexing.

Treatment	Initial Modulus		Breaking Strength		Elongation to Break		Energy to Break		Yield Load		Elongation at Yield		Plastic Modulus	
	$kg/cm^2 x10^{-3}$		kg		%		kg-cm		kg		%		$kg/cm^2 x10^{-3}$	
	W[1]	L[1]	W	L	W	L	W	L	W	L	W	L	W	L
Unflexed														
10% E-631	27.8	25.7	7.2	7.2	4.4	4.2	2.1	2.0	3.8	3.7	0.7	0.7	4.7	4.7
3% melamine	36.7	34.2	9.3	8.9	4.2	4.0	2.5	2.3	4.6	4.6	0.7	0.7	6.9	6.5
10% E-631 + 3% melamine	31.7	26.2	8.6	8.5	4.2	4.2	2.3	2.2	4.2	4.0	0.7	0.7	6.1	6.0
Beater addition[2] control	35.3	32.0	7.8	7.8	4.1	3.9	2.2	2.0	4.1	4.0	0.6	0.6	5.7	5.7
Regular control[3]	33.7	31.9	7.7	8.0	4.0	3.9	2.0	2.1	4.0	4.0	0.6	0.6	5.7	5.8
Flexed 1000 times over 3.18 mm rollers														
10% E-631	21.3	12.5	6.3	6.6	4.4	4.2	1.8	1.6	3.2	3.9	0.8	1.5	4.3	5.2
3% melamine	31.2	18.1	8.3	8.3	4.0	4.1	2.1	2.0	4.1	4.5	0.7	1.3	6.5	7.1
10% E-631 + 3% melamine	24.1	14.4	7.6	7.9	4.2	4.5	2.0	2.0	3.7	4.1	0.8	1.4	5.7	6.3
Beater addition[2] control	28.4	15.8	6.9	7.2	4.1	4.1	1.9	1.7	3.6	4.2	0.7	1.4	5.2	5.9
Regular control[3]	26.8	15.3	6.9	7.3	4.2	4.2	1.9	1.8	3.4	4.0	0.7	1.4	5.1	6.0

---

[1] W = width and L = length of flex samples.

[2] Handsheets made according to beater addition procedure but without acrylic and/or melamine resin.

[3] Handsheets made in conventional manner.

Table 10. The effect of treating wood pulp handsheets with acrylic resin E-631 and melamine wet strength resin on the retention of physical properties with flexing.

Treatment	Elmendorf Tear		MIT Fold Endurance		Cantilever Stiffness		Air Permeability	Weight per Unit Area
	g		1000 g double folds		g-cm		ml/min(10cm^2)	g/m^2
	W[1]	L[1]	W	L	W	L		
Unflexed								
10% E-631	84	85	1630	1790	2.4	2.3	870	78
3% melamine	76	82	1890	2260	2.7	2.6	713	70
10% E-631 + 3% melamine	79	74	2070	2380	2.6	2.6	615	75
Beater addition[2] control	86	93	1360	1600	2.3	2.4	602	70
Regular control[3]	93	82	1270	1470	2.4	2.2	540	69
Flexed 1000 times over 3.18 mm rollers								
10% E-631	76	88	1510	1430	1.1	0.9	948	
3% melamine	68	71	1970	1740	2.1	1.1	748	
10% E-631 + 3% melamine	66	69	1980	1910	1.9	1.0	644	
Beater addition[2] control	86	81	1170	1080	1.7	0.9	675	
Regular control[3]	92	81	1300	1270	1.6	0.8	612	

[1] W = width and L = length of flex specimens.

[2] Handsheets made according to beater addition procedure but without acrylic and/or melamine resins.

[3] Handsheets made in conventional manner.

Table 11. Standard deviation[1] for data in Table 9 on tensile properties of flexed and unflexed handsheets modified with acrylic resin E-631 and/or melamine wet strength resin.

Treatment	No. of Specimens		Initial Modulus		Breaking Strength		Elongation to Break		Energy to Break		Yield Load		Elongation at Yield		Plastic Modulus	
			$kg/cm^2 x 10^{-3}$		kg		%		kg-cm		kg		%		$kg/cm^2 x 10^{-3}$	
	W[2]	L[2]	W	L	W	L	W	L	W	L	W	L	W	L	W	L
							Unflexed									
10% E-631	6	6	1.1	2.1	0.4	0.4	0.3	0.2	0.2	0.2	0.4	0.3	0.06	0.08	0.4	0.5
3% melamine	6	6	2.2	2.6	0.4	0.4	0.2	0.5	0.1	0.3	0.2	0.3	0.04	0.07	0.5	0.9
10% E-631 + 3% melamine	6	6	1.0	1.7	0.4	0.3	0.2	0.2	0.2	0.2	0.5	0.2	0.05	0.14	0.4	0.3
Beater addition control[3]	6	6	1.1	1.9	0.6	0.2	0.3	0.3	0.3	0.2	0.2	0.2	0.02	0.03	0.5	0.6
Regular control[4]	6	6	2.1	2.7	0.4	0.8	0.2	0.3	0.2	0.3	0.1	0.3	0.03	0.03	0.3	0.5
							Flexed 1000 times over 3.18 mm rollers									
10% E-631	6	6	2.1	1.4	0.3	0.5	0.2	0.3	0.1	0.2	0.1	0.3	0.08	0.12	0.5	0.2
3% melamine	6	6	2.0	1.4	0.3	0.6	0.2	0.3	0.2	0.3	0.1	0.4	0.02	0.23	0.6	0.5
10% E-631 + 3% melamine	6	6	2.9	0.5	0.8	0.3	0.5	0.1	0.4	0.1	0.3	0.3	0.02	0.13	0.7	0.5
Beater addition control[3]	6	6	1.8	1.0	0.4	0.4	0.3	0.1	0.2	0.1	0.3	0.3	0.06	0.07	0.3	0.5
Regular control[4]	6	6	2.5	1.6	0.5	0.4	0.3	0.1	0.2	0.1	0.2	0.4	0.03	0.26	0.4	0.6

---

[1] $s = \sqrt{\frac{n\Sigma x^2 - (\Sigma x)^2}{n(n-1)}}$

[2] W = width and L = length of flex specimens.

[3] Handsheets made according to beater addition procedure but without acrylic and/or melamine resins.

[4] Handsheets made in conventional manner.

Table 12. Standard deviation[1] for the data in Table 10 on physical properties of flexed and unflexed handsheets modified with acrylic resin E-631 and/or melamine wet strength resin.

Treatment	No. of Specimens		Elmendorf Tear		MIT Fold Endurance		Cantilever Stiffness		Air Permeability
			g		1000 g double folds		g-cm		ml/min(10cm^3)
	W[2]	L[2]	W	L	W	L	W	L	
Unflexed									
10% E-631	6	6	10	8	221	487	0.2	0.2	72
3% melamine	6	6	10	11	314	436	0.3	0.1	64
10% E-631 + 3% melamine	6	6	9	5	234	421	0.2	0.1	57
Beater addition[3] control	6	6	9	7	221	354	0.1	0.2	47
Regular control[4]	6	6	12	5	372	385	0.1	0.2	52
Flexed 1000 times over 3.18 mm rollers									
10% E-631	6	6	6	11	363	195	0.1	0.03	59
3% melamine	6	6	7	15	477	214	0.1	0.04	47
10% E-631 + 3% melamine	6	6	5	6	193	506	0.2	0.04	67
Beater addition[3] control	6	6	13	9	210	234	0.1	0.06	45
Regular control[4]	6	6	14	9	294	363	0.1	0.02	43

---

[1] $s = \sqrt{\frac{n\Sigma x^2-(\Sigma x)^2}{n(n-1)}}$

[2] W = width and L = length of flex specimens.

[3] Handsheets made according to beater addition procedure but without acrylic and/or melamine resins.

[4] Handsheets made in conventional manner.

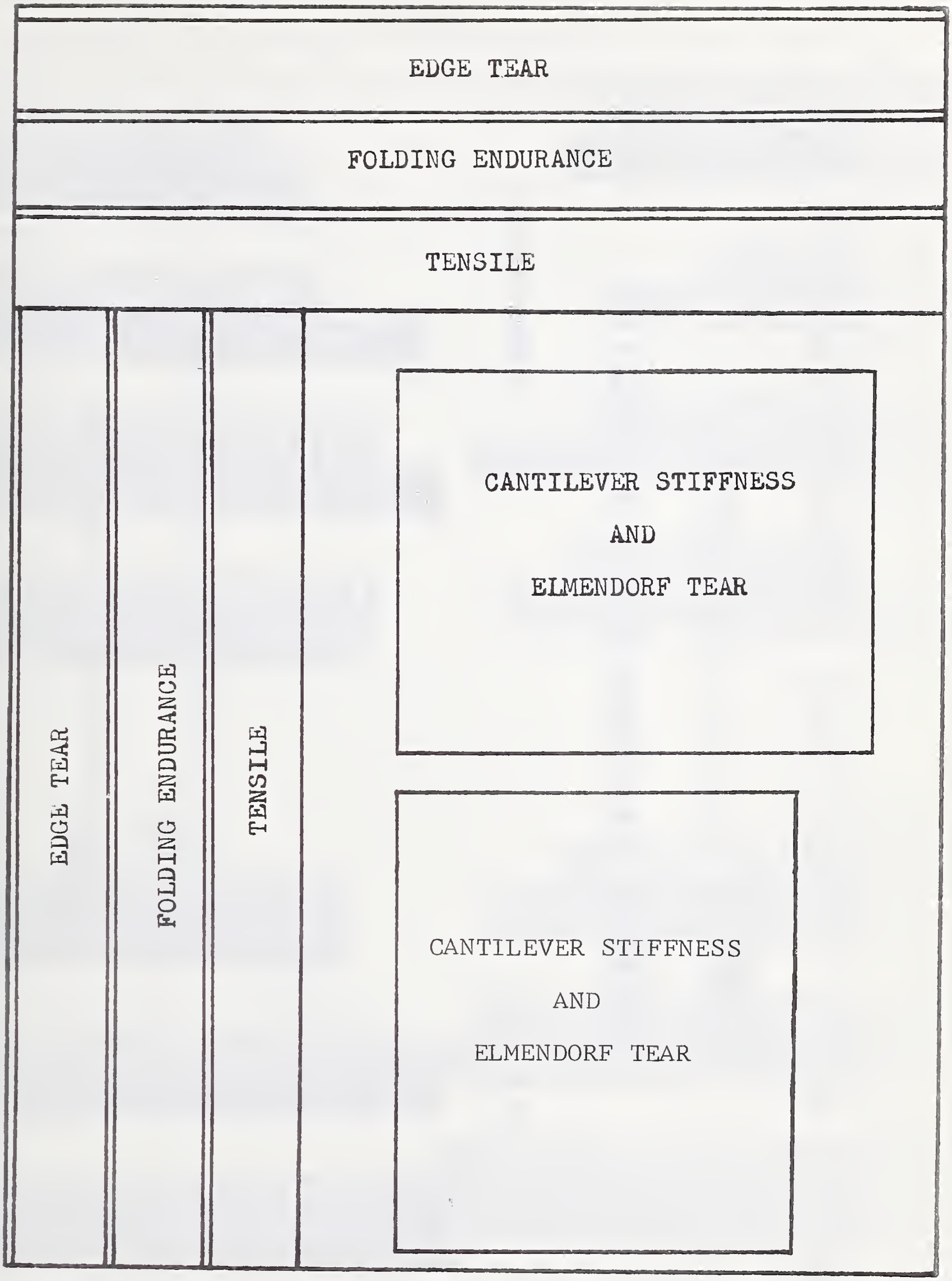


FIG. 1. SPECIMEN LAYOUT FOR FLEX SAMPLES

Fig.2

RETENTION OF CD PROPERTIES AFTER FLEXING IN CD

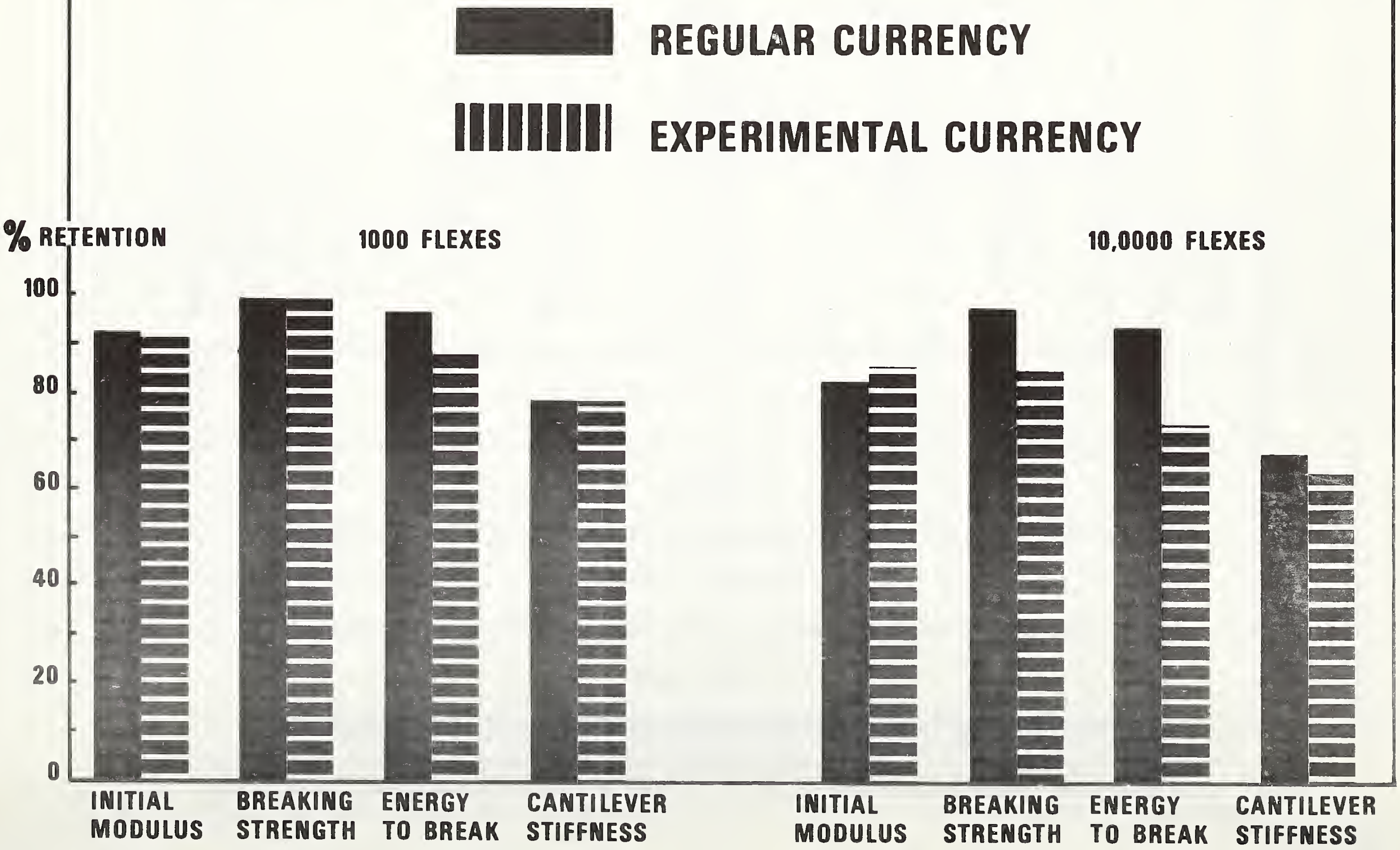
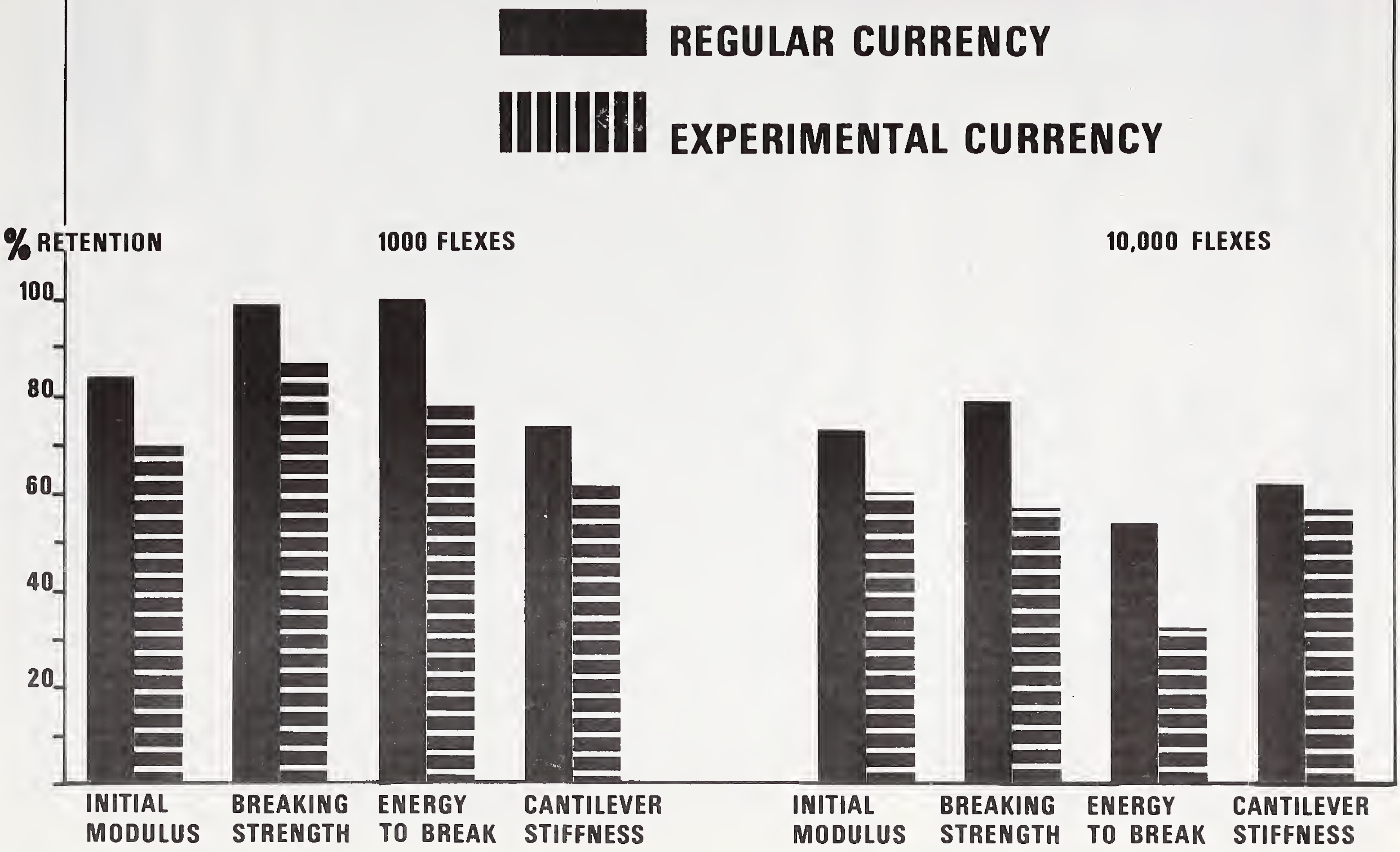


Fig. 3

RETENTION OF MD PROPERTIES AFTER FLEXING IN MD



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16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

As part of a continuing study for the Bureau of Engraving and Printing of the U.S. Department of the Treasury, two wood pulp papers (Paper A and Paper SDP) were evaluated for possible use in printing currency and an investigation was conducted to determine the feasibility of improving stiffness retention by modifying paper with a combination of acrylic resins and a wet strength resin. Currency printed on Paper A was comparable to present-day currency when flexed in the cross direction of the paper, but its performance was decidedly poorer when flexed in the machine direction. Further study is necessary before a firm recommendation can be made on the use of Paper A for currency.

Paper SDP showed poor retention of stiffness when flexed in either direction, but there are indications that, when treated with certain acrylic resins by the saturation technique, it might be suitable for currency paper. The significant decrease in paper density resulting from modifying pulp with acrylic resins by beater addition can be inverted by a second treatment with a melamine wet strength resin prior to paper formation. Preliminary data indicate that the double treatment can produce a paper having superior stiffness retention with flexing.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Acrylic resins; experimental currency paper; paper durability; paper structure; stiffness retention; wet strength resins.

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